Adapting Cropping Patterns to Climate Change

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Crops respond strongly to temperature and precipitation, and numerous studies indicate that projected changes in climate with increased atmospheric CO_2 will alter when, where and how crops are grown. Complex interactions of abiotic factors with pests, diseases, weeds and economic factors preclude an exact prescription of how climate change will affect agriculture, but there is immense value in understanding the basic aspects of possible effects. Two fundamental problems are to understand how plants may respond to the expected changes in the environment and how producers might adapt their farming practices to alleviate negative impacts and maximize the potential benefits.

Warmer temperatures usually accelerate development, resulting in earlier flowering and maturity. Warmer temperatures, however, also may allow a longer growing season if the length is otherwise delimited by early- or late-season low temperatures, including frosts. Most crops show a wide range of genetic variation for phenology, depending on their intrinsic earliness and responses to photoperiod or vernalization, so breeding likely will allow adaptive selection for crop phenologies that match changes in growing seasons. Temperature also affects potential growth and can induce acute stresses such as frost damage or heat stress. Further effects of temperature on soil processes and evapotranspiration can be expected, and although trends are less certain, climate change will also affect precipitation patterns.

Elevated CO_2 can enhance photosynthesis and reduce transpiration, resulting in increased yields and more efficient use of water. The responses are more pronounced in species possessing the C_3 mechanism than in C_4 and CAM species due to the CO_2 concentrating mechanisms of the latter two groups. Plants show numerous other responses to CO_2, including changes in phenology, leaf anatomy and dark respiration, but it is unclear whether these are direct responses to CO_2 or indirectly reflect effects of increased carbohydrate levels or decreased transpiration.

Attempts to assess potential impacts of climate change on agriculture, including options for adaptation, have largely focused on yield. However, potential changes in cropping patterns, involving both geographic distribution and temporal sequences, may require adaptive changes in research, marketing and processing. This paper describes two types of modeling that are useful in examining possible effects of climate change on cropping patterns. Ecological niche modeling, also known as bioclimatic envelope modeling, predicts the geographic distribution of a given species or population based on environmental factors assumed to influence its adaptation. Crop-simulation modeling uses quantitative descriptions of physiological processes to describe crop growth and development over time, allowing for influences of weather, soils and management. Thus, in addition to yield effects, simulations can provide valuable insights into how management, especially planting dates, and phenology might respond or be adapted to new production situations emerging from climate change.

Ecological Niche Modeling

The ecological niche of a population is its position in an ecosystem as delimited by abiotic and biotic factors. If geographic variation in these factors can be quantified and the population-specific limits defined for the factors, then the niche may be modeled and mapped. Effects of climate change on the geographic distribution of a given population are represented by remapping the niche using climate data that have been modified according to predictions from global or regional climate models.

The geographic distribution of a crop is modeled starting from data identifying locations where the crop is known to occur. This information is then linked to data on climatic, edaphic (soil), biotic or socioeconomic factors that are thought to delimit the geographic distribution of the crop. Climate data are of particular interest and are usually described through gridded (raster) surfaces. These are obtained by interpolating large sets of data from weather stations for variables such as mean monthly temperatures or total precipitation. The interpolations typically account for effects of elevation, and global sets of monthly data are available on a roughly 5-km (2.5 arc minute) grid *(e.g.*, Hijmans *et al.*, 2005).

There are numerous methods for modeling ecological niches, including environmental envelope techniques, classification tree analysis, generalized linear models, neural networks and genetic algorithms (Elith *et al.*, 2006; Heikkinen *et al.*, 2006). Methods differ in whether they consider only locations where the target organism is known to be present vs. methods that consider both presence and absence. Further differences include whether locations are assumed to be exact or to contain measurement error and whether spatial autocorrelation is considered.

The BIOCLIM method as implemented in the DIVA-GIS software package (Hijmans *et al.*, 2001) provides a useful introduction to niche modeling because of its simplicity. A set of location data is obtained, and through preliminary analyses, a set of explanatory climate variables are selected, such as total annual precipitation or mean minimum temperature of the coldest month. An envelope (multidimensional space) is defined, the dimensions of which correspond to the factors being considered. The border of the

envelope corresponds to the upper and lower limits of each variable as determined from the locations where the species is known to occur. Regions outside the envelope are coded as completely unsuitable. Within the envelope, zones of increasing suitability are identified based on the portion of locations that would fall within a given range of the climate variables. The climate variables are represented through gridded surfaces, where each cell for a given variable has a unique value. In defining the envelope, the cells within the 20–80 percentile range are considered to have "excellent" suitability, cells within the 10–20 or 80–90 percentile ranges have "very good" suitability, and so on to the 100 percentile limit.

Geographic Distribution of Wheat in North America

Based on geographic and temporal patterns, three classes of wheat crops in North American are conventional spring wheats, fall-sown winter wheats and winter-sown spring wheats. Conventional spring wheats mainly occupy the coldest, northernmost regions where winter survival of winter wheats is low due to cold stress, which may involve drought effects and amount of snow cover. The northern edge of winter-wheat distribution reflects conditions where the season is too short for economic production and risks of frost injury or winter drought stress are high. Winter wheats cover a large belt extending to the Gulf Coast. Their vernalization requirement ensures that after fall establishment, they remain vegetative until favorable growth conditions return in the spring. Over-wintering also requires cold tolerance. Key climatic limits along their southern margin are whether the winters are cool enough to vernalize the crop and whether temperatures during grain filling are mild enough to ensure good yields. Winter-sown spring wheats are found in southern regions, mainly in California and Arizona where risk of frost injury is low. We emphasize that while these broad patterns hold, local circumstances including biotic stresses and options for crop rotations also can affect the choice of wheat system.

To help guide wheat research across continents, the International Maize and Wheat Improvement Center (CIMMYT) developed a formal classification of global wheat megaenvironments (MEs) (Rajaram and van Ginkel, 2001; Hodson and White, 2007). Within this system, the traditional spring-wheat environments are ME6, and the fall-sown, irrigated spring-wheat environments are ME1. A logical expectation is that global warming will result in ME1 and ME6 shifting northward. Working from a database of locations classified by ME, the various climate variables available with DIVA-GIS were examined to determine which variables best delimited the respective MEs. For ME1, which was delimited by the mean temperature and total precipitation of the coolest quarter and the mean minimum temperature of the coldest month, the modeled historical distribution agreed well with the location data (Fig. 1A), although the modeled distribution extends further eastward, suggesting a need to consider whether rainfall levels are low enough to require irrigation.

A set of climate data for the year 2100 is available for DIVA-GIS, based on the National Center for Atmospheric Research climate model CCM3 simulations (Govindaswamy *et al.*, 2003). The criteria used to delimit ME1 were applied to the grids for the future

climate, thus producing a map of the projected distribution of ME1 (Fig. 1B). In the western United States, the most striking difference was that ME1 is predicted to cover a larger area of the Central Valley of California. At the same time, however, the ME1 region along the western coast of Mexico is much reduced. The map also suggests that winter-sown spring wheats could be grown along a much wider band along the US Gulf Coast, but it should be noted that the analysis does not consider possible pest and disease problems, which are more prevalent in humid regions.

A similar analysis was conducted for ME6 considering four climate variables (Fig. 2). The mean maximum temperature in the warmest month was used to exclude regions with excessive summer temperatures, and the mean temperature in the warmest quarter was intended to ensure that the growing season was warm enough for wheat. The mean temperature of the coldest quarter was used to identify regions where winters are too severe for survival of winter wheats. Finally, the total precipitation in the wettest quarter was used to test whether there was enough summer moisture for production. The most striking changes with climate change were that suitable areas largely disappeared in the continental United States and that the regions classified as excellent were displaced both northward and westward, making parts of Alberta especially suitable. It is noteworthy that the displacement of ME6 northward should correspond to an expansion in the area suitable for winter wheat, so, without further analysis, it is difficult to assess the net impact on total wheat area.

These analyses are subject to various improvements. The list of sites should be expanded both for current wheat-producing locations and for sites where wheat is not grown. A more accurate delimitation of ME1 would require consideration of access to irrigation, which likely will be reduced by climate change. Elevated CO_2 can increase canopy temperature and reduce water use, and adjustments likely are needed to reflect these effects. Suitability of soils and terrain should also be assessed since regions that are suitable climatologically may otherwise prevent production. Heikkinen *et al.* (2006) have reviewed additional issues in niche modeling under climate change.

Crop-Simulation Modeling

Crop-simulation models are widely used to predict impacts of climate change on agricultural production, including in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (Easterling *et al.*, 2007). Their ability to integrate effects of weather, soils and crop management, and predict changes in a wide range of crop and soil parameters, makes them logical choices for investigating the potentially complex interactions among environment and crop management. Most applications of models in climate-change research have emphasized impacts on individual crops and mainly considered changes in economic yield. In regions where climatic conditions permit year-round cropping, however, changes in potential planting dates and crop durations may allow important adaptive changes in cropping patterns. The ability of simulation models to predict how yield and phenology change with planting dates make them highly suitable for examining temporal changes in crop sequences. Before illustrating a simple example for irrigated systems in Arizona, a brief description of simulation models is given.

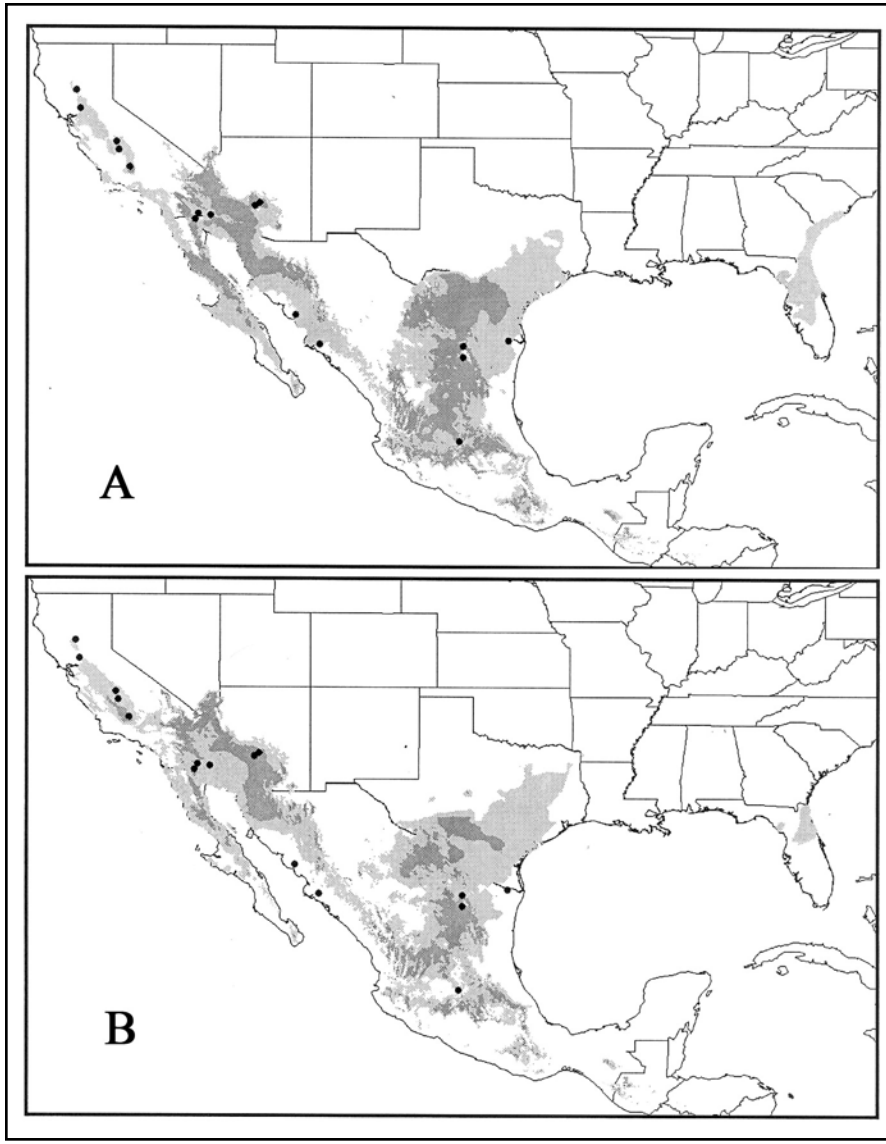

Figure 1. Distribution of wheat megaenvironment 1 (ME1) of the CIMMYT classification for winter-planted, irrigated spring types in North America as modeled with the BIOCLIM tool of DIVA-GIS (Hijmans *et al.*, 2001). Points indicate locations classified as belonging to ME1, and shaded regions indicate good to very good (light gray) or excellent (dark gray) suitability. A: Based on historical climate data. B: Based on modeled climate for 2100.

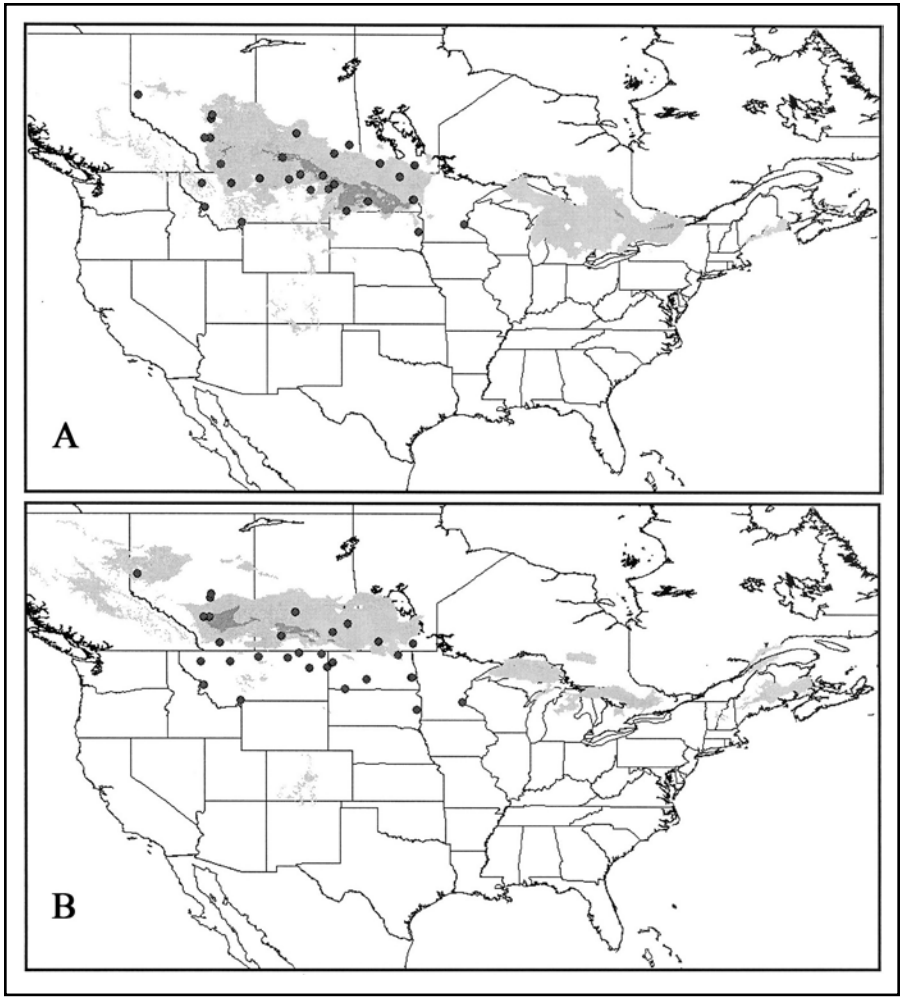

Figure 2. Distribution of wheat megaenvironment 6 (ME6) of the CIMMYT classification for traditional spring types in North America as modeled with the BIOCLIM tool of DIVA-GIS (Hijmans *et al.*, 2001). Points indicate locations classified as belonging to ME6, and shaded regions indicate good to very good (light gray) or excellent (dark gray) suitability. A: Based on historical climate data. B: Based on modeled climate for 2100.

Simulation Models

Simulation models quantify key processes of crop growth and development as influenced by weather, soils, management and the genetic attributes of the plant (at the species or cultivar level). Information on these factors is provided as inputs to the model. From soil

initial conditions and planting information, the model estimates increments of growth and development, which are integrated over time, typically using hourly or daily time intervals. Growth is described as the balance of gains through photosynthesis and losses due to respiration and senescence. The rate of photosynthesis may vary with light interception, temperature, CO_2 and the water and nutrient status of the crop. Respiration may depend on temperature and the metabolic activity of the tissue, which is often related to tissue-protein concentrations. The cost of biosynthesis of tissues varies with their composition—cellulose, starch, sugars, lignins, lipids, proteins and other components—which also contributes to net respiration.

Development usually involves predicting a series of phenological stages such as seedling emergence, floral initiation, anthesis and physiological maturity. These are modeled by assuming that intrinsic developmental rates are modified by temperature, photoperiod or other factors. Often, differences in the intrinsic rates and in photoperiod response are key determinants of the ability of a model to represent genetic differences among cultivars.

Information on development guides a set of rules used to partition growth among different organs. In seed crops prior to anthesis, priority is given to leaf growth, but water or nutrient deficits may increase allocation of assimilate to roots. Post-anthesis growth gives increasing priority to fruits or seeds, often involving remobilization of assimilate and nitrogen from vegetative tissues. To simulate effects of water and nutrients, additional procedures are used to estimate levels of water and nutrients in the soil and their availability to the crop. This may involve extensive modeling of soil and atmospheric processes.

The simplest models estimate daily growth using a concept of radiation-use efficiency, while the most complex models calculate photosynthesis, transpiration and energy fluxes on sub-hourly time scales. Hay and Porter (2006) review the underlying physiology embodied in different models, and Tsuji *et al.* (1998) describe a series of related models and their applications to diverse problems, including climate-change research.

Simulating Cropping Sequences under Climate Change: Cotton, Sorghum and Wheat in Arizona

Both hot- and cool-season annual crops are grown in the irrigated, arid croplands of Arizona. For summer crops, heat stress and very high water use are potential concerns and might be exacerbated under climate change, but warmer spring or fall conditions might improve conditions for cropping outside of the period of peak summer heat. For winter crops especially, reduced frequency and severity of frost injury might allow a longer cropping season. Yield responses to planting date for three crops, cotton, sorghum and wheat, are compared to illustrate how shifts in the cropping season of one crop might affect options for the other crops. The analyses include a climate-change scenario of +1.5°C for daytime temperatures, +3.0°C for nighttime temperatures, and 580 ppm CO_2, approximating a "business as usual" scenario for 2100.

For cotton (Fig. 3), the simulations suggest that although warming will lengthen the growing season, it would result in a much more bimodal response to planting date, with planting dates from mid-March to late May producing lower yields. Elevated CO_2 largely compensates for the yield reduction. Although the highest yields are for February

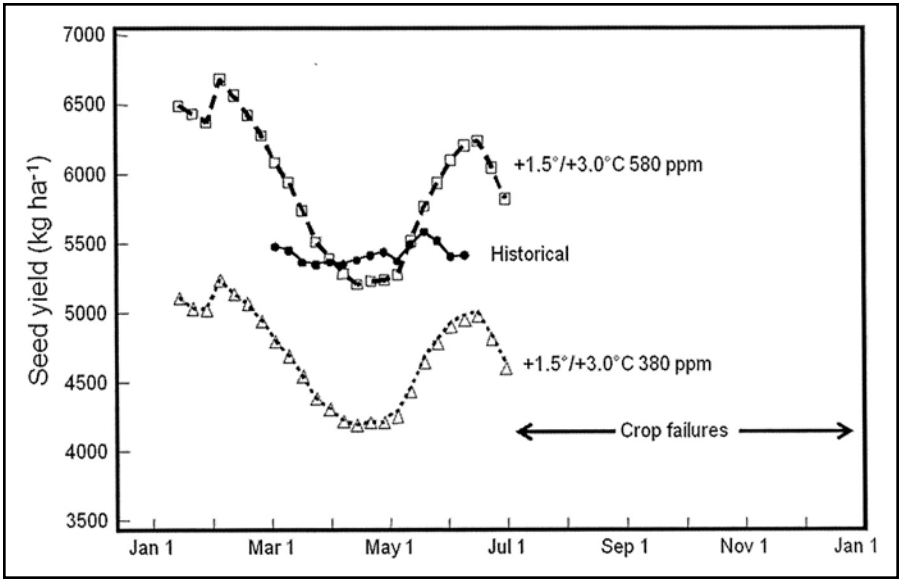

Figure 3. Response of cotton-seed yield to planting date at Maricopa, AZ, as simulated by the CSM-CROPGRO-Cotton model. Historical values are means of results from 1987 to 2008 and assume a CO_2 of 380 ppm. Planting dates with no yield correspond to crop failures due to low temperatures.

plantings, a mid-June planting offers high yield with an increased possibility of planting a winter crop. Thus, Figure 4 compares crop yields and durations for cotton, sorghum and wheat under climate-change and historical scenarios. The specific planting dates were selected allowing for flexibility in order to obtain near maximum yields while permitting a wider range of cropping options. Cotton planted in mid-June and reaching maturity in early November leaves time for a December-planted wheat. The wheat would mature by late May, potentially allowing a cotton-wheat rotation. Such rotations are widespread in northwestern India and in Pakistan (Mayee *et al.*, 2007), and a cotton-barley rotation is already used in Arizona.

Although early-planted sorghum could be grown slightly earlier, it would still overlap with both wheat and cotton, thus precluding annual rotations. The slight loss of sorghum yield with climate change reflects the low responsiveness of C_4 crops to elevated CO_2 plus a shorter growth duration. For all three crops, it is likely that fine-tuning of phenology might improve net annual economic yield of the systems.

Opportunities for Plant Biology

While the two types of modeling may seem remote from agricultural biotechnology, there are important avenues for plant biology to improve our ability to predict crop phenotypes from the interacting effects of genotypes, environmental factors and management prac-

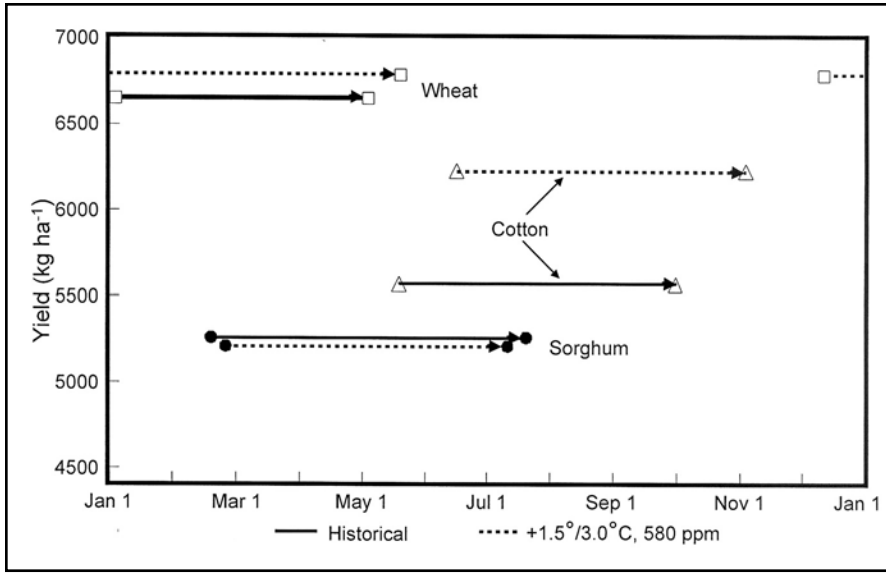

Figure 4. Relations among yields, planting dates and harvest dates for cotton, sorghum and wheat at Maricopa, AZ, simulated for historical weather data from 1987 to 2008 or a climate change scenario of an increase in daily maximum temperature of 1.5°C and an increase in minimum of 3.0°C and a CO_2 concentration of 580 ppm. For cotton and wheat, the combinations of planting dates and yields for climate change were selected considering tradeoffs between yield and options for double cropping.

tices. These include improved characterization of cultivars and refining the physiological assumptions of the models.

Simulation models typically represent cultivar differences through cultivar-specific parameters for traits like photoperiod sensitivity, earliness *per se* and representative grain size. The parameters are evaluated through an iterative process of adjusting their levels until simulations of traits such as time of anthesis and grain number per unit area adequately match values obtained in field trials. Efforts to estimate the parameters based on the genetic makeup of cultivars show promise (White *et al.*, 2008), but they have been constrained by the lack of information on loci affecting traits used as model parameters and by the scarcity of accurate data on the genetic makeup of cultivars when loci are known. Although plant biology has vastly improved our ability to identify and characterize loci, increased focus on traits relevant to ecophysiological models is needed.

A second avenue is for plant biology to improve the understanding of underlying processes, thus allowing the simulation models to describe plant responses more accurately. For example in modeling phenology, there is uncertainty over when a plant becomes sensitive to photoperiod and whether photoperiod sensitivity persists after floral initiation. Studies of temporal variation in mRNA levels of key loci involved in control of flowering should

clarify how to model photoperiod responses, possibly also suggesting key diagnostic tests in field experiments. Clarification of how plants sense CO_2 levels, such as in the response of guard cells to CO_2, might indicate whether a common mechanism underlies effects of CO_2 on phenology, leaf structure and dark respiration that are not yet considered in crop-simulation models. Numerous other examples could be mentioned and, indeed, much of plant biology dealing with photosynthesis, respiration, development and plant responses to abiotic stresses is potentially of value for guiding how specific processes are modeled.

Conclusions

The potential impacts of climate change on cropping patterns are highly researchable but present significant methodological challenges. The examples for wheat regions of North America and cropping systems in Arizona demonstrate that climate-change impacts are not simply a question of increased or decreased productivity. The impacts may have dramatic effects on land use as well as cropping practices in a given region. Ecological niche modeling and crop-simulation modeling are powerful, complementary tools for examining the spatial and temporal aspects of climate-change impacts. Their successful application, however, requires effective interdisciplinary collaboration, including participation from plant biology.

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JEFFREY WHITE is a plant physiologist who emphasizes use of ecophysiological models and geospatial tools to understand how crops respond to environment. He obtained his training at Harvard College and the University of California-Berkeley. His early research on common bean, conducted at the International Center for Tropical Agriculture (CIAT) in Colombia, emphasized understanding the physiological and genetic bases of cultivar differences in yield potential, adaptation to water deficits, and responses to photoperiod and temperature. Achievements at CIAT included identifying two major loci controlling photoperiod response and demonstrating that higher yield under drought was associated with greater extraction of soil moisture, which depended on traits controlled by genes expressed in the roots.

Moving to the International Maize and Wheat Improvement Center (CIMMYT) in Mexico in 1995, he established the first GIS and crop modeling laboratory. His group revised CIMMYT's mega-environment classifications for maize and wheat research, and successfully promoted use of geospatial tools at national and regional scales such as for efforts to develop drought-tolerant maize in eastern and southern Africa. In 2003, Dr. White joined USDA-ARS in Arizona, where he works on predicting crop response to global change, continuing his work with models and geospatial tools.

He has (co)authored over sixty journal papers and supervised fifteen MSc and PhD theses.